

On the Estimation of the Number of Upward Flashes From Wind Turbines in Mountainous Areas

Smorgonskiy Alexander, Farhad Rachidi
EMC Laboratory
EPFL
Lausanne, Switzerland
alexander.smorgonskiy@epfl.ch

Marcos Rubinstein
IICT
HEIG-VD
Yverdon-les-bains, Switzerland
rubinstein.m@gmail.com

Gerhard Diendorfer
OVE Service GmbH, Dept. ALDIS
Vienna, Austria
g.diendorfer@ove.at

Abstract—Lightning incidence analysis is required for the design of adequate lightning protection systems for wind turbines. We present a method to estimate the number of upward flashes for multiple wind turbines located in mountainous areas. The proposed method is applied to the case of the Mont Crosin wind turbine park located in the Jura mountains in the Northwestern part of Switzerland. A significant increment of the number of upward flashes was observed with the installation of new power units.

Keywords—wind turbines; lightning; lightning detection systems; upward flashes

I. INTRODUCTION

The estimation of the lightning incidence to wind turbines is an important task required for the evaluation of lightning risks and for the design of appropriate protection systems. The lightning incidence for simple cases of individual wind turbines located on flat terrain is covered in the standard IEC 61400-24 [IEC, 2010]. However, wind turbines are often located on mountain ridges and are grouped into wind turbine parks. These situations are not directly addressed in the IEC standard and they require the development of advanced methods of observation, for example those, involving lightning location systems as discussed by [Garolera *et al.*, 2012]. Moreover, a high incidence of upward flashes initiated from wind turbines can be expected in such locations. This type of flashes results in significant damages to the wind turbine components, especially the blades, as discussed in [Yasuda and Yokoyama, 2011; Ishii *et al.*, 2012].

In this paper, we present a method to estimate the number of upward flashes for multiple wind turbines located in

mountainous areas. The proposed approach is based on the method developed previously in [Smorgonskiy *et al.*, 2011] for lightning incidence studies for single tall structures.

This paper is structured as follows: after this introduction, Section II describes the area of study located in the Jura mountains in Switzerland. In Section III, a description of the lightning data used for this analysis is given. In Section IV, the number of upward flashes from a single tall structure is evaluated. In Section V the variation of the annual incidence to the wind turbines is evaluated. Final conclusions are given in Section VI.

II. AREA OF STUDY

The area of Mont Crosin is a part of the Jura Mountains in the Northwestern part of Switzerland. Mont Crosin Ridge (with a highest altitude of 1263 m) is located opposite to Mount Chasseral (altitude 1607 m).

In 1996, the construction of the wind turbine park in the area of Mont Crosin in Switzerland began with the installation of three Vestas V44 wind turbines with 600 kW of installed capacity each. The wind turbine park is in constant evolution. The site, shown in Fig. 1, now hosts the largest wind turbine park in Switzerland consisting of 16 wind turbines with a total installed capacity of about 30 MW.

It can be also seen from Fig. 1 that there are several other tall structures found in the area of study. The first one is the antenna on the Chasseral Mountain, constructed in 1945 and afterwards replaced by a new antenna (114-m tall) in 1983.

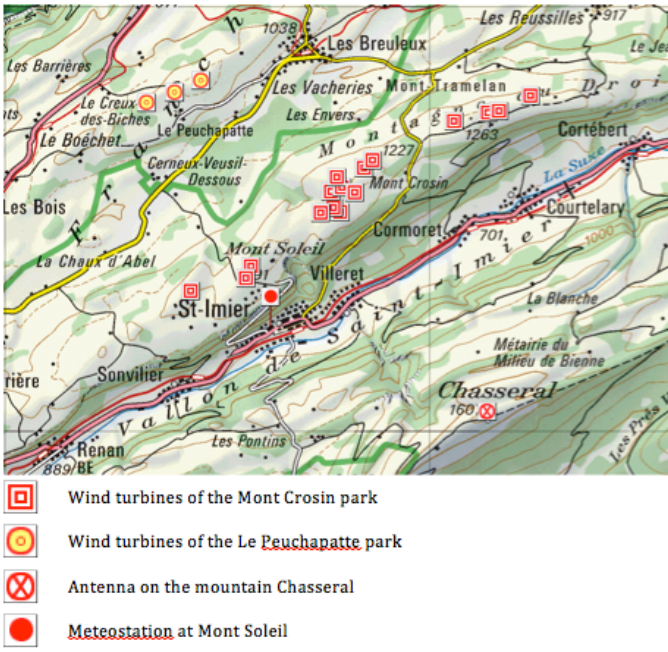


Fig. 1. Location of tall structures in the Mont Crosin area.

A small wind turbine park located near Le Peuchapatte consisting of three units was built at the end of 2010. All three wind turbines are Enercon E82 and measure a height of 150 m including the tower and the blades.

It is known that wind turbines and other tall structures placed on mountains and hills are frequently struck by lightning since their effective height is greater than that of a standing object of the same physical height on flat terrain [Eriksson, 1978].

III. LIGHTNING INCIDENCE IN THE AREA OF STUDY

During almost 13 years of observations (01/01/2000 – 12/11/2012), the EUCLID lightning location system has registered 7349 flashes within the area of study measuring 225 km². A representation of the ground flash density for 1 km² cells is shown in Fig. 2. The average ground flash density over the whole area is $N_g = 2.5$ flashes/km²year.

Variations from the average value are observed within the area of study as shown in Fig. 2. The smaller variations are mainly due to the random nature of lightning occurrence. However, larger variations of N_g , sometimes more than by a factor of 2, are also observed. Several reasons may contribute to these variations. On the one hand, it was shown in [Smorgonskiy et al., 2013b] that within the area of study, the lightning flash density increases with altitude. On the other hand, the largest variations are mainly due to the initiation of upward flashes from the tall structures: telecommunication towers and wind turbines.

Direct evaluation of the influence of the presence of these structures on the lightning incidence is not possible from the density map shown in Fig. 2 since (1) the values of N_g represent time averages over 13 years or so and (2) a uniform grid division is not suitable for such analysis since the positions

of the tall objects can be so close to the boundary between cells that strikes to the object may fall on different adjacent cells.

IV. EVALUATION OF THE NUMBER OF UPWARD FLASHES TO THE CHASSERAL TRANSMITTER

We will illustrate the method of estimating the number of upward flashes developed previously in [Smorgonskiy et al., 2011] considering the example of the Chasseral transmitter. Since it is an isolated object, a direct application of the method is possible: The number of upward flashes is obtained by properly scaling the difference between the local ground flash density at the transmitter and the average ground density in its vicinity. It can be evaluated using the following equation:

$$N_{up} = (D_1 - N_g) \cdot S_1 \quad (1)$$

where

- N_g is the average value of the ground flash density in the area (2.5 flashes/km²year),

- D_1 is the lightning flash density evaluated within a circle of 1 km radius around the transmitter, which has a surface S_1 .

The obtained value for N_{up} is 27 flashes/year. This value should be corrected by a factor of 2 to take into account upward flashes composed of initial continuous current only, which constitute about 50% of the total upward flashes observed at lightning research towers and are not detected by lightning location systems [Smorgonskiy et al., 2013a]. This factor 2 is in agreement with direct lightning current observations at the Gaisberg Tower in Austria [Diendorfer, 2015].

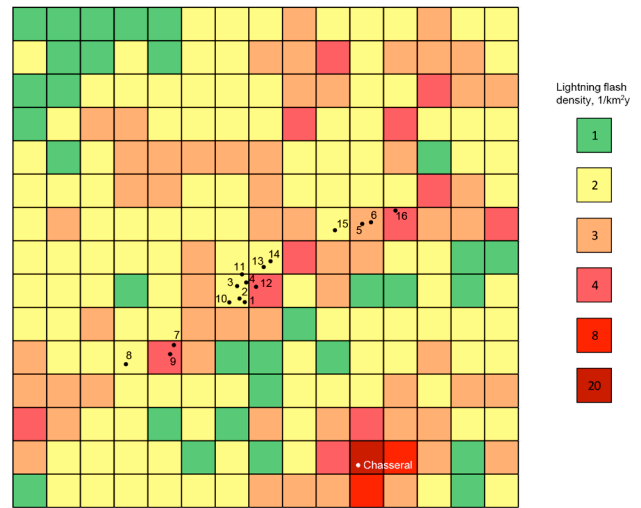


Fig. 2. Lightning flash density map in Mont Crosin area (grid cell size is 1 km x 1 km)

V. ESTIMATION OF THE NUMBER OF UPWARD FLASHES FROM THE MONT-CROSLIN WIND TURBINES

The proximity of the wind turbines belonging to the Mont Crosin park does not allow the direct application of the method illustrated in the previous section to evaluate the number of

upward flashes. We therefore propose in what follows a modification to the original method.

Firstly, 1-km radius circles are drawn around each turbine. Since the wind turbines are located in the immediate vicinity from one another, these circles intersect as shown in Fig. 3, forming three clusters with several wind turbines in each of them as defined in Table 1.

TABLE I. WIND TURBINE CLUSTERS

| Cluster | Wind turbines (year of installation) | Area, km ² |
|---------|--------------------------------------|-----------------------|
| 1 | 7-8 (2004), 9 (2010) | 6.20 |
| 2 | 1-4 (1996-98), 10-14 (2010) | 7.43 |
| 3 | 5-6 (2001), 15-16 (2010) | 5.95 |

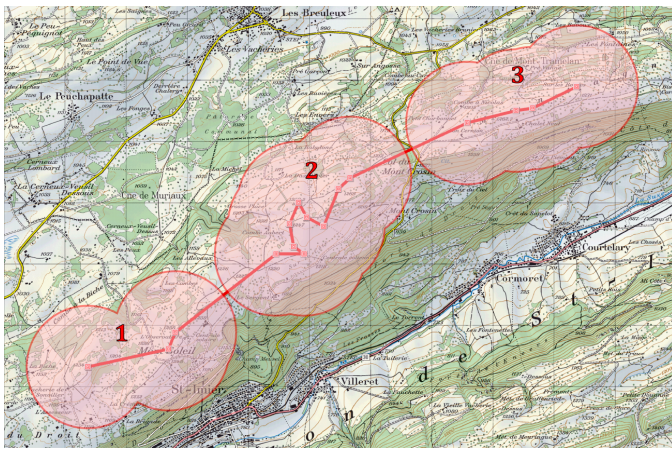


Fig. 3. Three clusters of wind turbines as defined in Table I.

Secondly, since the wind turbines were installed over the period between 1996 and 2010, the analysis of upward flashes in each cluster was performed on an annual basis in order to identify the variations in the upward flash incidence following the construction of the wind turbines. The resulting histogram for Cluster #1 is shown in Fig. 4. The developed approach will be demonstrated for that cluster, within which there were no wind turbines in the period before 2004. From Fig. 4, the value of N_{g1} for this cluster can be derived: $N_{g1} = (11.4 \pm 4.5) / 6.2 = 1.8 \pm 0.7$ flashes/km²year, which is slightly smaller than the average lightning flash density in the area reported in Section III. After 2004, when two 100-m tall wind turbines were installed in this cluster, the average lightning flash incidence has increased; this significant rise can be attributed essentially to the upward flashes from the wind turbines. The difference between the mean annual number of flashes in the two periods 2000-2004 and 2005-2010 provides an estimate of the number of upward flashes from those two wind turbines: 5.9 flashes/year, as reported in Table II. Again, this value should be corrected by a factor of 2 to take into account upward flashes composed of initial continuous current only as discussed in Section IV.

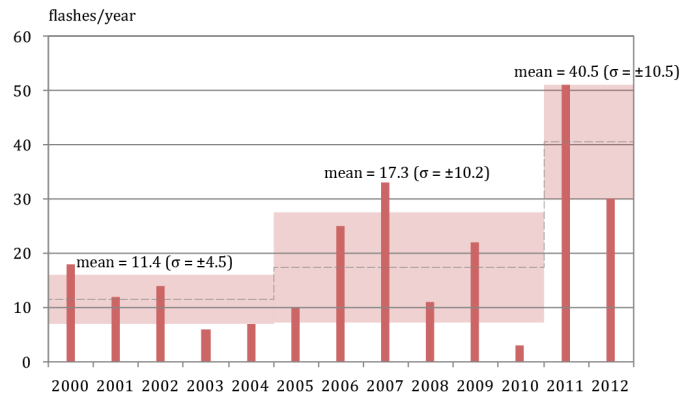


Fig. 4. Annual number of flashes registered by the LLS within Cluster #1.

Finally, in 2010, another 140-m tall wind turbine was installed. As can be seen from Fig. 4, the number of flashes in this cluster has again increased. This time, the mean number of upward flashes from the three wind turbines of Cluster #1 was found to be 29.1 flashes/year.

The developed method was applied to the other two clusters as well. In Cluster #2, there was no time period without wind turbines. Four wind turbines of 67 m height were constructed in 1996-98 before the available observation period of the EUCLID lightning location network. In 2010, 4 taller wind turbines, measuring 140 m, were added in this cluster.

In Cluster #3, during 9 years of the observation period, there were only 2 wind turbines of 76 m height each. Two other wind turbines of 140 m height were constructed in 2010.

The obtained variations in lightning incidence are reported in Table II. As for Cluster #1, the lightning incidence in clusters #2 and #3 increased significantly after the installation of new wind turbines.

TABLE II. UPWARD FLASHES INCIDENCE WITHIN WIND TURBINE CLUSTERS

| Cluster | Periods of observation | | |
|---------|--|--------------------------------|--------------------------------|
| | Number of upward flashes: mean (standard deviation), flashes/year | | |
| 1 | 2000-2004 (0 wind turbines) | 2005-2010 (2 wind turbines) | 2011-2012 (3 wind turbines) |
| | - | 5.9 ($\sigma = \pm 6.5$) | 29.1 ($\sigma = \pm 10.5$) |
| 2 | 2000-2010 (4 wind turbines) | | 2011-2012 (8 wind turbines) |
| | 4.0 ($\sigma = \pm 7.6$) | | 17.4 ($\sigma = \pm 13.0$) |
| 3 | 2000-2001 (0 wind turbines) | 2002-2010 (2 wind turbines) | 2011-2012 (4 wind turbines) |
| | - | 7.1 ($\sigma = \pm 9.2$) | 24.1 ($\sigma = \pm 2.0$) |

VI. CONCLUSIONS

A new method was developed to estimate the number of upward flashes from wind turbines in mountainous areas. The method is based on the analysis of lightning location system data and, therefore, it does not require direct lightning current measurements at the wind turbines, which is an advantage of this method and allows its straightforward application to different areas.

To method was applied to a configuration with multiple wind turbines in the Jura mountains. It was found that, within the area of study, the largest number of upward flashes is initiated from an antenna located on Mount Chasseral, 5 to 10 km away from the wind turbines. It was also shown that the installation of new power units resulted in a significant increase in the number of upward flashes in the area of study.

Due to the compact location of wind turbines within the clusters, it is not possible to determine the number of upward flashes to a given wind turbine. However, continuous improvements of lightning location systems in terms of detection efficiency and location accuracy may allow in the future to tighten the clusters around individual wind turbines and to increase the accuracy of the proposed method.

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